Adaptive Energy Efficient Communications for Hybrid Aerial-Terrestrial Systems

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***Abstract*—Aerial telecommunications networks based on Low Altitude Platforms (LAPs) are expected to optimally meet the urgent needs of emergency relief and recovery operations for tackling large scale natural disasters. The energy efficient operation of such networks is important given the fact that the entire network infrastructure including the battery operated ground terminals, exhibit requirements to operate under power constrained situations. In this paper, we propose and evaluate a real-time adaptive transmission strategy for dynamic selection of direct and cooperative links based on the channel conditions for improved energy efficiency. We show that the cooperation between mobile terrestrial terminals on the ground could improve the energy efficiency in the uplink depending on the temporal behavior of the terrestrial and the aerial uplink channels. The simulation analysis corroborates that the adaptive transmission technique improves the overall energy efficiency of the network.**

***Index Terms*—Aerial network infrastructures; emergency communications; Low altitude platforms (LAP); energy efficiency; cooperative communications.**

I. Introduction

In the wake of a disaster, emergency communications are instrumental to implement a carefully planned and coordinated relief response and must be supported by a reliable infrastructure. However, the existing telecommunications infrastructure is likely to be left damaged, at least in part, and may then become largely inoperable. These considerations have restored increased interest in flexible and inter–operable emergency telecommunication systems [1] where speed of deployment and self–sustainability, both in terms of operations and energy support, are major challenges. Due to their ability to access affected areas which may prove difficult to reach otherwise, aerial platforms, and more particularly low altitude platforms (LAPs), are expected to offer an efficient alternative for supporting emergency communications [1], [2], [4], [5]. Depending on multiple factors including the type of aircraft (e.g. lighter-than-air or airfoil-based), choices made for the antennas and radio technologies, available power for the payload and intended relief missions, a LAP can be operated at elevations between a few dozens to a few thousands meters. Moreover, due to their payload flexibility, relatively fast deployment times and low propagation delays, LAPs are envisioned to quickly restore communications in the affected zones in complement to existing terrestrial recovery infrastructures [6].

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A particular attention must be paid to the energy efficiency of this integrated LAP-terrestrial communication infrastructure. As the power grid itself may be affected in the considered area, the entire infrastructure, including the ground stations, may be energy-constrained and equipment survivability may therefore be a major issue. Besides, the communication link between the ground devices and the LAP is a significant cause of energy consumption as the devices need to spend higher power in the uplink communication with the LAPs, which can worsen with the availability and the quality of the related channels.

In this context, we study the means to extend the survivability of the wireless devices by designing and implementing adaptive cooperative relaying strategies. In [3], we presented a preliminary analysis for the hybrid HAP (High Altitude Platforms)-terrestrial systems for an uplink Rayleigh fading channel, which we further refined in [6] with an analytical result for an uplink Ricean channel. We have shown that this latter model is more realistic for LAP-terrestrial communication scenarios with LOS conditions. In this paper, we design a real-time adaptive transmission scheme which estimates channel conditions and selects accordingly either direct or cooperative links. We evaluate its energy efficiency and show that the cooperation between mobile terrestrial terminals on the ground could improve the energy efficiency in the uplink depending on the temporal behavior of the terrestrial and the aerial uplink channels.

The rest of the paper is organized as follows. In Section II, we present the communication model for the terrestrial and the uplink terrestrial-LAP channels. In Section III, we analyze the required power from the direct- and relay-based transmissions from the source node to the LAP for a given bit error probability, and then discuss how energy efficiency can be improved accordingly. In Section IV, we present an adaptive and energy efficient scheme that enables a node to either transmit through direct or relay links, in real time and depending on the channel conditions to achieve a predefined bit error probability. Section V discusses the simulation results and related performance analysis of our scheme and finally section VI concludes the paper.

II. Communication Model

The communication model and protocols for the terrestrial channel and the uplink terrestrial-LAP channel models are

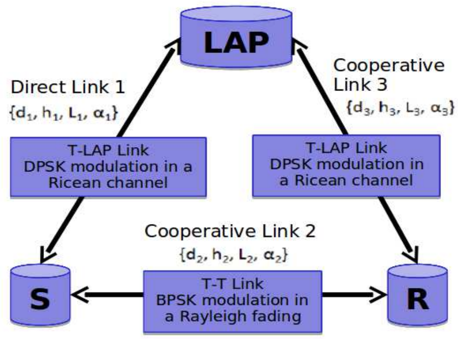


Figure 1: Scenario for Hybrid LAP-Terrestrial communications with cooperative relay links

presented in this section. The channel models and the related parameters for the hybrid LAP-Terrestrial system with a single terrestrial source (S), relay (R) and destination D (which is the LAP) is depicted in Fig. 1. In our model, h_i with $i \in \{1, 2, 3\}$ are the small scale fading gains, α_i are the pathloss exponents, d_i are the T-R distances and L_i are the mean pathloss for the respective links as sown in the figure.

We consider a Rice uplink channel model with α_1 and α_3 pathloss exponents from the two terrestrial terminals to to the LAP. The corresponding channel gains for the S $\rightarrow$ LAP and the R $\rightarrow$ LAP tend to vary over time based on the spatial separation. For the terrestrial radios we consider a Rayleigh channel model with a pathloss exponent of α_2. The pathloss is given by $L_i(d_i) = L_i(d_0)\left(\frac{d_i}{d_0}\right)^{\alpha_i}$, where $L_i(d_0)$ is the pathloss at a reference distance d_0 which is given by the free-space pathloss [7] $L_i(d_0) = (4\pi f_i d_0/c)^2$, where $c = 3 \times 10^8$ is the speed of light and f_i is the carrier frequency. The mean channel power gains are given by $\gamma_i = \frac{1}{t}\int_0^t h_i^2(t)dt$. Note that for the Ricean uplink channels, the channel gains γ_1 and γ_3 contain both the direct-path and the multi-path component signal gains. Moreover, we consider BPSK modulation for the terrestrial links and and DPSK for the terrestrial-LAP uplinks, the corresponding received signals for the communication links described in Fig.1 can be expressed in general as $r_i(t) = \frac{1}{L_i(d_i)}h_i(t)s_i(t) + \upsilon_i(t)$, where $s_i(t)$ are the transmitted signals and $\upsilon_i(t)$ are the corresponding additive Gaussian noise components at the receivers with a double-sided power spectral density of $N_0(i)/2$. The corresponding probability of error for the terrestrial link and the terrestrial-LAP links are respectively given by [7],

$$\Pi_i = 0.5\left(1 - \sqrt{\frac{\Gamma_i}{(1+\Gamma_i)}}\right) \quad \text{for } i = 2 \text{ only, and} \qquad (1)$$

$$\Pi_i = \frac{1+K_i}{2(1+K_i+\Gamma_i)}\exp\left(\frac{-K_i\Gamma_i}{\Gamma_i+1+K_i}\right) \quad \text{for } i = 1, 3 \qquad (2)$$

where K_i is the Rice factor [7], $\Gamma_i = E_b(i)\gamma_i/N_0(i)$ is the mean received SNR for the i^{th} link, $E_b(i)$ is the received bit energy given by $E_b(i) = P_t(i)G_i^tG_i^r/[\Delta_i L_i(d_i)]$, G_i^t and G_i^r are the transmit and receive antenna gains, $P_t(i)$ is the transmit signal power, and Δ_i(bits/s) is the data rate for link i. In the relay link with the decode and forward strategy the relay node R receives the signal $r_2(t)$ from S detects it and transmits to the LAP (destination). In the direct link, the LAP directly receives the signal $r_1(t)$ from the source node S. We note here that the communication terminals are enabled with multi-radios allowing them to easily communicate with the LAP and the other existing terrestrial radios. In Fig. 1 for example, links 1 and 3 can be of a particular radio technology and link 2 can be of another technology allowing the terrestrial nodes to cooperate with each other.

III. Assumptions

Context aware capabilities are required in order to gather all the parameters used by the network model. In our scenario, these capabilities are acquired easily through the use of gossip protocols. Since the exchange of the context information is required only between nodes within one hop distance (see Fig. 1). Many gossip protocols have been proposed for wireless ad hoc networks, and most of them are based on some variants of flooding according with the network density [10], [11], [12]. Additionally, many gossip approaches have been studied, where only the nodes within some region broadcast or forward a message with some probability, to reduce the overhead in the network [13], [14].

The design and implementation of context aware capabilities in the network however is beyond the scope of this paper and is subject to future work. For ease of implementation, we consider that all the ground terminals have access to the communication from the LAP platform in the downlink mainly receiving broadcast information which could be used for periodic dissemination of the context aware information about the radio network. Moreover, in the network model, we assume that the nodes exchange context information periodically meaning that the channel, communication and network parameters corresponding to the participating nodes are known to each other. Hence, the above mentioned parameters such as the T-R separations d_i, the channel power gains γ_i, the pathloss exponent α_i are all assumed to be known and updated periodically by the terrestrial nodes.

IV. Energy Efficient Communication with QoS Constraints

In this section we present how the energy efficiency can be improved for the communication between the terrestrial and LAP terminals. First we analyze the required power for the direct and relay based transmissions from the source node to the LAP for a given bit error probability (QoS) and then see how energy efficiency can be obtained. In our subsequent analysis we consider the communication model described in the previous section, the presented analysis however can be generalized for an arbitrary cooperative communication model in general.

A. Power Requirements for the Direct Link

The minimum power requirement for the direct link with a bit error constraint, ξ is calculated here. By considering the bit error expression in (2) for the direct link, the transmit power requirement $P_t(1)$ at node S can be iteratively computed using

the Gradient Descent method for some $\epsilon_1 > 0$ and $\Pi_1 = \xi$ given by,

$$\hat{P}_{t_{n+1}}(1) = \hat{P}_{t_n}(1) - \epsilon_1 \Lambda(\hat{P}_{t_n}(1)) \quad (3)$$

where, $\Lambda(\hat{P}_{t_n}(1))$ (from equation (2)) is given by,

$$\Lambda(\hat{P}_{t_n}(1)) = \frac{d[\xi - \Pi_1(P_t(1))]}{dP_t(1)} = \frac{BV_1V_2[V_1K_1+1]}{[1+K_1+\Gamma_1]}$$
$$V_1 = \frac{1+K_1}{2[1+K_1+\Gamma_1]} \quad , \quad V_2 = \exp\left(\frac{-K_1\Gamma_1}{1+K_1+\Gamma_1}\right) \quad (4)$$

and $B = \frac{G_1^t G_1^r \gamma_1}{L_1(d_1)N_0(1)\Delta_1}$.

B. Power Requirements for the Relay Link

The overall bit error probability for the $S \rightarrow R \rightarrow LAP$ communication based on the decode and forward cooperative strategy depends on the communications between $S \rightarrow R$ and $R \rightarrow$ LAP. If Π_2 and Π_3 are the bit error probabilities respectively of the sequential transmission $S \rightarrow R \rightarrow LAP$ the overall error probability is then given by $\overline{\Pi} = \Pi_2(1-\Pi_3) + \Pi_3(1-\Pi_2)$. Since the probability values are small, $\overline{\Pi}$ can be simplified to be $\overline{\Pi} = \Pi_2 + \Pi_3$. Then using (1) and (2) the overall bit error rate for the relay transmission is given by,

$$\overline{\Pi} = 0.5\left(1 - \sqrt{\frac{\Gamma_2}{(1+\Gamma_2)}}\right) + \frac{1+K_3}{2(1+K_3+\Gamma_3)} \times \exp\left(\frac{-K_3\Gamma_3}{\Gamma_3+1+K_3}\right) \quad (5)$$

Considering the above equation, the transmit power requirement $\{P_t(2), P_t(3)\}$ at the source and relay nodes respectively for a bit error constraint of ξ is given by,

$$P_t(2) = \frac{L_2(d_2)N_0(2)\Delta_2\lambda^2}{G_2^t G_2^r \gamma_2(1-\lambda^2)} \quad (6)$$

where λ is a function of the relay transmit power $P_t(3)$ given by,

$$\lambda = (1-2\xi) + \frac{1+K_3}{(1+K_3+\Gamma_3)}\exp\left(\frac{-K_3\Gamma_3}{\Gamma_3+1+K_3}\right) \quad (7)$$

with $\Gamma_3 = \frac{G_3^t G_3^r \gamma_3 P_t(3)}{L_3(d_3)N_0(3)\Delta_3}$.

The optimum power allocations between S and R that would minimize the overall power consumption for the given bit error rate ξ should be computed and the corresponding transmit power values at S and R should be used. Considering equation (7) the optimum power can be found by minimizing β w.r.t $P_t(3)$ or equivalently given by,

$$\{\hat{P}_t(2), \hat{P}_t(3)\} = \arg\min_{P_t(3)} \{P_t(2) + P_t(3)\} \quad (8)$$

Note that $P_t(2)$ is a strictly decreasing function in the domain of $P_t(3)$ and given that $P_t(3)$ is a strictly increasing (linear and convex) function in its own domain the summation $X = P_t(2) + P_t(3)$ becomes convex. Since $X = P_t(2) + P_t(3)$ is a convex function in the domain of $P_t(3)$. Therefore, the minimum of X in $P_t(3)$ would provide the optimum power allocation $\{\hat{P}_t(2), \hat{P}_t(3)\}$ for the source and relay nodes. From equations (6) and (7), the first derivative of X is given by,

$$\frac{dX}{dP_t(3)} = 1 + \frac{dP_t(2)}{dP_t(3)} = 1 - \frac{2\lambda A_0 A_1 U_1^2 U_2}{[1-\lambda^2]^2} \quad (9)$$

where,

$$A_0 = \frac{L_2(d_2)N_0(2)\Delta_2}{G_2^t G_2^r \gamma_2} \quad , \quad A_1 = \frac{G_3^t G_3^r \gamma_3}{L_3(d_3)N_0(3)\Delta_3}$$
$$U_1 = \frac{1+K_3}{[1+K_3+\Gamma_3]} \quad , \quad U_2 = \exp\left(\frac{-K_3\Gamma_3}{1+K_3+\Gamma_3}\right) \quad (10)$$

and $\lambda = (1-2\xi) + U_1U_2$. The optimum relay power $\hat{P}_t(3)$ is then given by,

$$\frac{dX}{dP_t(3)}_{|_{P_t(3)=\hat{P}_t(3)}} = 1 - \frac{2\lambda A_0 A_1 U_1 U_2(U_1K_3+1)}{[1+K_3+\Gamma_3][1-\lambda^2]^2} = 0 \quad (11)$$

Here, again we consider the Gradient Descent method to solve for $\hat{P}_t(3)$ from the above equation for some $\epsilon_2 > 0$. The solution for $\hat{P}_t(3)$ is then given by,

$$\hat{P}_{t_{n+1}}(3) = \hat{P}_{t_n}(3) - \epsilon_2 \frac{d^2X}{dP_t^2(3)}_{|_{P_t(3)=\hat{P}_{t_n}(3)}} \quad (12)$$

The optimum transmit power $\hat{P}_t(2)$ at S is given by substituting $\hat{P}_t(3)$ in equation (6) to obtain $\{\hat{P}_t(2), \hat{P}_t(3)\}$ for minimum power consumption in the cooperative link.

C. Energy Efficiency Factor - β

Let us define an energy efficiency factor β to compare the energy efficiency between the direct and relay links,

$$\beta \triangleq \frac{[P_t(2) + P_t(3)]}{P_t(1)} \quad (13)$$

Based on (13) we see that when $\beta > 1$ the direct link becomes more energy efficient than the relay link, when $\beta < 1$ the relay link becomes more efficient than the direct link, and when $\beta = 1$ both relay and direct links become equally energy efficient. Note that in our theoretical analysis we ignore the energy consumptions due to processing at the nodes as it is assumed to be a constant for all the terrestrial nodes.

V. Real-Time Adaptive Hybrid Terrestrial-LAP Transmission for Energy Efficiency

Based on the theoretical model developed in the previous section we present an adaptive algorithm for the source node to communicate with the LAP energy efficiently by choosing between the relay and the direct links depending on the communication channel conditions to achieve a predefined bit error probability. We use the following notation throughout the section for illustrating the algorithm:

- T_x is the transmission power for the interface.
- $P_t(1)$ is the source T_x for the aerial-interface.
- $P_t(2)$ is the source T_x for the Terrestrial-interface.
- $P_t(3)$ is the relay T_x for the Terrestrial-interface.

Alg. 1 describes the pseudocode for the Adaptive transmission power scheme. It calculates the optimal power allocation for the cooperative link.

Algorithm 1 Adaptive transmission power scheme.

Procedure at the source
if $Queue$ is not empty **then**
  BER = calculateBER[$P_t(1)$,SNR_1]
  $P_t(3)$ = calculatePt[BER,SNR_2,SNR_3]
  $P_t(2)$ = calculatePt[$P_t(3)$,SNR_2,SNR_3]
  if $P_t(1) \leq P_t(2) + P_t(3)$ **then**
    T_x = $P_t(1)$
    p = Queue.next()
    sendDirectLink(p)
  else
    T_x = $P_t(2)$
    p = Queue.next()
    sendCooperativeLink(p)
  end if
end if
Procedure at the relay
if receive(p)=relay packet **then**
  T_x = $P_t(3)$
  sendDirectLink(p)
end if

Procedure at the source: Firstly, when the source has a packet to be transmitted, it calculates the bit error rate (BER) for the uplink source-LAP using $P_t(1)$ and the channel conditions of the direct link. In order to minimize the overall power consumption, the source calculates the optimum power allocation $P_t(3)$ for the relay using the BER of the uplink source-LAP and the channel conditions of the cooperative link. Further, the source calculates $P_t(2)$ for the source using $P_t(3)$ and against the channel conditions of the cooperative link. Finally, the source decides to choose the cooperative link or the direct link for power efficiency. If $\{P_t(2)+P_t(3)\} \geq P_t(1)$ the source sets its T_x equal to $P_t(1)$ and sends out the packet to the LAP through the direct link. Otherwise, if $\{P_t(2)+P_t(3)\} < P_t(1)$ the source sets its T_x equal to $P_t(2)$ and sends out the packet to the LAP using the cooperative link.

Procedure at the relay: When the relay receives a packet, it sets its T_x equal to $P_t(3)$. Then, the relay immediately sends out the packet to the LAP through the direct link.

VI. Simulation Results and Analysis

In this section, we present results from the performance evaluation of the energy efficient adaptive transmission power scheme for hybrid LAP-terrestrial networks, implemented in a link level simulator. The implementation of the framework and the experiments were performed using Omnet++[15], a link level simulator, with the INETMANET framework.

A. Simulation Environment

We implemented the hybrid LAP-Terrestrial network model and the adaptive transmission power scheme described in the previous sections in order to evaluate the power efficiency of the cooperative, non-cooperative and adaptive systems under different scenarios. In order to implement the terrestrial and LAP terminals, we considered a simple two-layer hierarchical architecture. The first module simulates the behavior of a simple Application Layer while the second module simulates the Physical Layer of the nodes/devices.

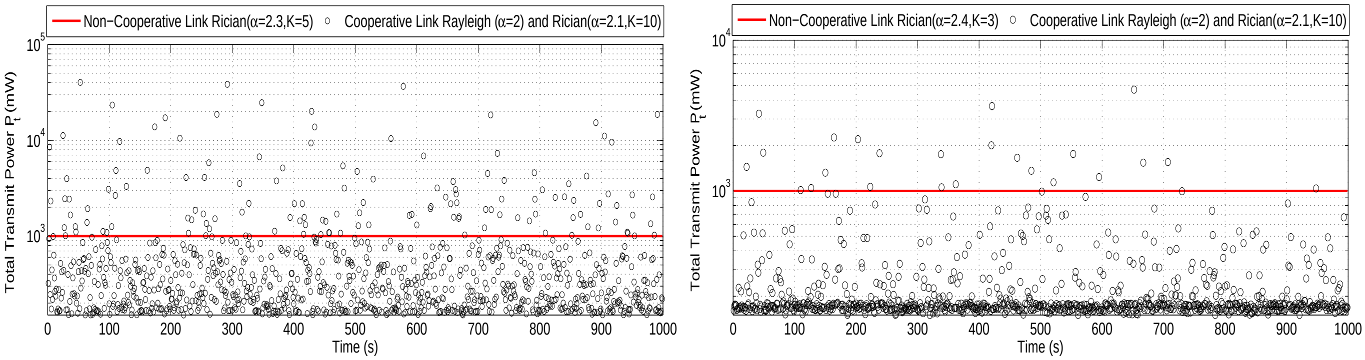
The Physical Layer module is composed of two interfaces: (i) the first interface simulates the terrestrial-terrestrial link (T-T) using BPSK modulation in a Rayleigh fading channel with a pathloss coefficient and (ii) the second interface simulates the terrestrial-LAP (T-L) link using DPSK modulation in a Ricean channel as described in [6]. The context aware capabilities of the terminals are simulated using the $Blackboard$ module. This module allows nodes to share their information with the other nodes in the network. Therefore, the $Blackboard$ module contains information about the localization and physical configuration of the nodes, the channel conditions of the different links and others.

The *adaptive transmission power scheme* is implemented in the Application Layer module using the information coming from $Blackboard$ module and Alg. 1. Firstly, the source calculates the BER ξ_1 for the uplink source-LAP using the transmission power $P_t(1)$. Further, the source calculates the optimum power allocation $P_t(2)$ for source and $P_t(3)$ for relay in order to minimize the overall power consumption for the given bit error rate ξ_1. Finally, the source decides to choose the cooperative link or the direct link for power efficiency using the next policy: *If* $\{P_t(2) + P_t(3)\} < P_t(1)$ *then the source chooses the cooperative link.*

The simulation scenario with channel parameters for the hybrid LAP-Terrestrial system is sketched in Fig. 1. The scenario considered a total of 3 terminals simulating the source (S), relay (R) and destination (LAP) nodes in a two-dimensional plane for $S = \{0, 0\}, R = \{1000, 0\}, LAP = \{500, 4000\}$. The scenario environment is static (without mobility) throughout the whole simulation. The other parameters are: maximum transmission power= 4000 mW, datarate = 6 Mbps, carrier frequency = 3.5 GHz, transmit antenna gain = receive antenna gain = 3 dB, the thermal Noise for TT link= -110 dBm, the thermal Noise for TL link= -130 dBm and receiver sensitivity = -110 dBm. The S Application Layer unicasts 1 UDP packet of $1000 bytes$ every $1s$ to the LAP during $1000s$.

B. Testing Methodology and Results

Initially, we considered two scenarios for the simulations using good and medium uplink $S \rightarrow LAP$ channel conditions in order to study the relative energy efficiency performance for a given bit error probability.Good and medium channel conditions basically means that the channel has variations in the SNR and BER from low to high values. This can happen for several reasons i.e. the presence of obstacles between nodes, the distance, the presence of external interference etc. For the simulations, we obtained good and medium channel conditions by varying the pathloss exponents α and the the Ricean factor K. The first simulation scenario clearly has a better uplink channel from $S \rightarrow LAP$ compared to the second simulation scenario. It is important to remark that when the values of the alpha and K are constant for a link, it does not mean that the channel conditions are essentially static. These values, in general, denote that one link is better or worse than the other link. However, the quality of direct and cooperative



(a) Scenario$_1$ (b) Scenario$_2$

Figure 2: Total transmit power calculated by the direct and cooperative links, before to apply the adaptive transmission power scheme, Vs. time for scenario$_1$ and scenario$_2$ (Y axis is in logarithmic scale).

channels varies, since the channel power gain for each link is a variable value in time (see Sec. II). The channel power gains are used in order to calculate the SNR and BER using the respective channel propagation model. Therefore, the SNR and BER for the links are not constant.

Fig. 2 shows the total transmit power calculated by the non-cooperative and cooperative links , before applying the adaptive transmission power scheme, Vs. time for scenario$_1$ and scenario$_2$. Here, the total transmit power level was kept constant $P_t(1) = 1000mW$ for the direct transmissions and variable $\{P_t(2) + P_t(3)\}$ for the cooperative transmissions. Since the channel is variable over the time, the total transmit power required for transmission by the cooperative link for a given bit error rate ξ_1 is also changed over time. Therefore, the *adaptive transmission power scheme* allows the source to choose dynamically the direct link or the cooperative link based on the channel conditions in order to save energy. In other words, the source chooses the cooperative link for all the P_t values under the red line. As we can see in the Fig. 2, the cooperative link has better energy efficiency performance for both the scenarios.

We derive the energy efficiency performance based on the results obtained in Fig. 2 by computing β over the time for all scenarios. The corresponding cumulative distribution function for the energy efficiency performance β is shown in Fig. 3. For scenario$_1$ which has a better direct uplink channel than scenario$_2$, we observe that the energy efficiency factor β is under 1 for the 88% of the samples. On the other hand, for scenario$_2$ which has a poorer direct uplink channel the energy efficiency factor β is under 1 for the 99% of the samples. In Fig. 4 we plot the probability distribution function of β based on the results obtained in Fig. 3. From the figure, we can conclude that (i) there is a higher probability that the beta values are concentrated around smaller values (more or less 0.1-0.4) and (ii) when the non-cooperative channel is poorer than cooperative channel, the PDF of beta increases for the smaller values (more or less 0.1-0.4). Therefore, we can assess intuitively that the cooperative communication link gives better energy efficiency for both the considered scenarios.

Since our objective is to evaluate the energy efficiency of the non-cooperative, cooperative and adaptive systems, the energy consumption is evaluated at the Physical Layer assuming a

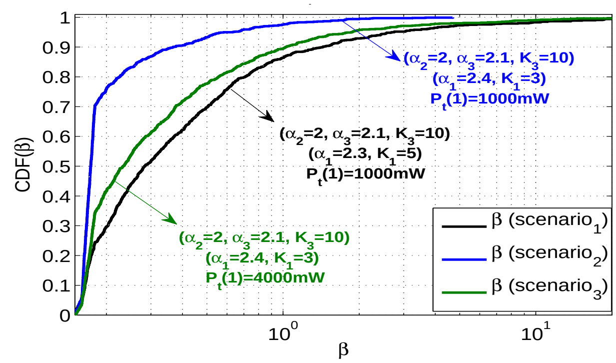


Figure 3: Comparing the energy efficiency between the direct and cooperative links by observing the cumulative distribution function of β for scenario$_1$, scenario$_2$ and scenario$_3$ (X axis is in logarithmic scale).

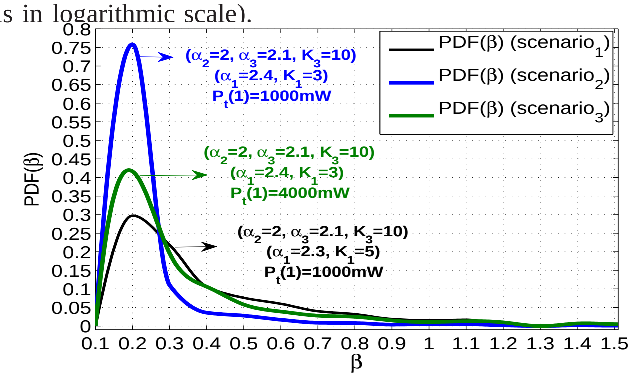


Figure 4: The probability distribution function of β.

unit voltage level and hence by measuring the current over time. We have assumed that the maximum transmit power of each device is 4000 mW. Therefore, when the transmit power of the cooperative link increases beyond this threshold, the source sets P_t to 4000 mW. We also fixed the energy consumption for the reception at $0.03\mu J/bit$ [16], [17], [18]. Therefore, the energy consumption results for scenario$_1$ and scenario$_2$ (scenario$_3$ will be explained further on) are depicted in Fig. 6 in order to evaluate the effects of channel conditions over the total energy consumption of the network for the non-cooperative, cooperative and adaptive systems. It is important to note that the terrestrial and LAP nodes/devices have a simple two-layer hierarchical architecture and thus, the overhead introduced by the MAC and Network Layer are not considered

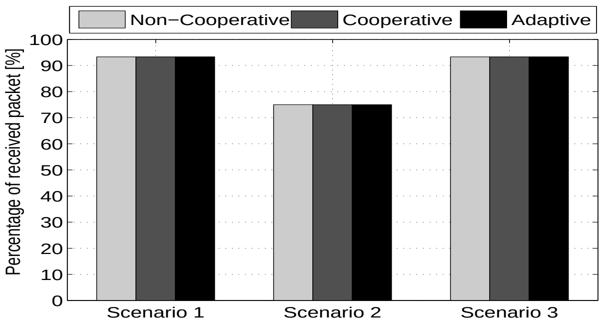


Figure 5: Percentage of received packet for the non-cooperative, cooperative and adaptive systems

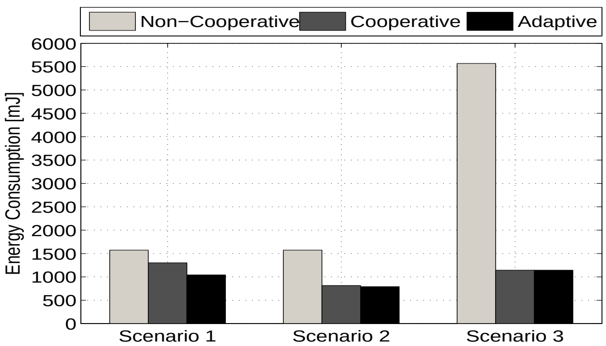


Figure 6: Total energy consumption of the network for the non-cooperative, cooperative and adaptive systems

in our energy model. In terms of energy consumption, the results in Fig. 6 show that the adaptive system performs better than the cooperative and non-cooperative systems for both the scenarios. Fig. 5 shows the percentage of received packet for the non-cooperative, cooperative and adaptive systems. The percentage of received packets is the same for non-cooperative, cooperative and adaptive system because for the relay link from $S \rightarrow R \rightarrow LAP$ the transmit power pair $P_t(2), P_t(3)$ requirement at the source and relay respectively is calculated for the same BER of the link from $S \rightarrow LAP$ calculated with $P_t(1)$.

Finally, the scenario$_3$ considered similar settings as in scenario$_2$. Compared to scenario$_2$, here, $\mathrm{P}_t(1)$ is increased to 4000 mW in order to achieve the same QoS as obtained in scenario$_1$ (see the percentage of received packet in Fig. 5). As a consequence, the BER of the direct link decreases and the QoS is improved. From Fig. 6, we can observe that the total energy consumption of the network for the cooperative and adaptive systems remains more or less equal for all scenarios. However, the energy consumption for non-cooperative system in scenario$_3$ increases in comparison to the scenario$_1$ and scenario$_2$. This is due to the fact that, under the same SNR, cooperative links can be far more reliable than direct links and it requires less transmission energy for the same BER requirements.

VII. Conclusions and Future Work

In this paper, we proposed a real-time adaptive transmission scheme which dynamically selects the best link based on the channel conditions for enabling energy efficient communications in hybrid aerial-terrestrial networks. We showed that the cooperation between mobile terrestrial terminals on the ground improves the energy efficiency in the uplink depending on the temporal behavior of the terrestrial and aerial uplink channels. The simulation results confirmed that the adaptive transmission scheme shows efficient and reliable performance with respect to the energy consumption when compared to cooperative transmission and direct transmission techniques. As a future work, we are currently extending our adaptive transmission model to analyse the energy efficiency of cooperative strategies in network topologies with multiple LAPs and multiple relay links. Besides, we are evaluating possible adaptations for the energy efficiency factor, β and the influence of battery capacities of terrestrial terminals on relay selection in multi-LAP aerial-terrestrial systems.

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